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Power generation with biogas from municipal solid waste: Prediction of gas generation with *in situ* parameters

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ABSTRACT

Estimations of biogas emissions in final disposal sites have been studied by several researchers, primarily for their potential as a renewable source of energy and greenhouse gas emissions mitigation. Different models have been developed to predict the generation of biogas; the first-order model is widely used. Most of these models are based on two parameters, the methane generation rate (k) and methane generation potential (L_0). These parameters cannot be generalized for biogas estimation in any site, and must be modified according to *in situ* characteristics. The objectives of this research are (a) modify the constants of k and L_0 with *in situ* data, and (b) estimate the biogas generation in a sanitary landfill of a Mexican city using the modified constants. The following data were used in modifying the model constants biogas: (a) waste characterization studies, (b) biogas extraction tests, (c) observations of characteristics and sanitary landfill operation, (d) interviews with the managers of the sanitary landfill, and (e) several parameters of the Intergovernmental Panel on Climate Change (IPCC) model. Biogas estimation using the modified constants was performed in the version 2.0 Mexico Landfill Gas Model proposed by Stearns, Conrad and Schmidt Consulting Engineers, Inc. (SCS Engineers). The results show that approximately 70% of the waste generated is organic, which influences the value of the parameters used in calculating the k and L_0. With *in situ* characteristics, values of $k=0.0482\ yr^{-1}$ and $L_0=94{,}457\ m^3/t$ were obtained. It is projected that the electric power generation could reach a maximum capacity of 2.4 MW in 2019. This energy could increase the installed capacity in the Ensenada by approximately 4.36% and supply approximately 66% of the electric energy required for lighting, which amounts to savings of US$2.62 million and an environmental benefit of approximately 1.17 Mt CO_2e from 2009 to 2025.

Contents

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1. Introduction

Biogas produced in landfills (landfill gas, LFG) is the result of physical, chemical, and microbial processes that occur in the waste. Due to the organic nature of most wastes, microbial processes govern the process of biogas generation. These processes are sensitive to their environment, and therefore, there are a number of factors that affect the microbial population and thus, the biogas generation. The main components of biogas are methane (CH_4), carbon dioxide (CO_2), and traces of several other compounds [1–4]. Estimations of biogas emissions in final disposal sites (FDS) have been studied by several researchers [1–3,5–13], primarily for their potential as a renewable source of energy and greenhouse gas emissions mitigation.

LFG use for power generation is now a near-commercial technology, as it represents a certain amount of energy resource and can cover a certain percentage of energy demand. Nowadays, several LFG exploitation projects have been identified worldwide, most of them in the United States (US) and in Europe. Landfills can be regarded as conversion biogas plants to electricity, not only covering internal consumptions of the facility but contributing in the power grid, as well. A LFG plant consists of a recovery and a production system [2]. LFG is pumped from vertical wells (perforated piping in bulk of waste) and guided in well stations by horizontal pipes that connect each well with one well station. In well stations, LFG is rounded up and transmitted by primary horizontal network in the electric power station. There, LFG is treated (dehumidification, de-sulphurised, or other) and after is supplied in the generator unit for combustion and electric power production [2,5,14]. Extracted LFG data from studies on landfills show a wide range of possible LFG production, between 0.05 and 0.40 m^3/kg of waste [3,5–7,15].

LFG as one of the major sources of energy can be used to provide electricity energy and is a good option to be used in internal combustion generators, turbines, microturbines, fuel cells and other power producing facilities as well [14,16,17].

The electricity production with LFG on landfills is realized with internal combustion engines. These engines are the most widely used technology for the conversion of LFG to electricity [2,14,16,18] and are primarily used at sites where LFG production can generate 0.10–3 MW of electricity [14,18,19], or where sustainable LFG flow rates to the engines are approximately 30–2000 m^3/h at 50% CH_4 [14,16]. Between 500 and 540 m^3/h of LFG at 50% methane is necessary to generate 1 MW of electricity [18]. For sites able to produce more than 3 MW of electricity, additional engines may be added [14,18]. When operated on LFG, engine power ratings are commonly reduced by 5–15% compared to operation on natural gas [2]. Advantages of this technology include low capital cost, high efficiency, and adaptability to variations in the LFG output [14,16,18].

Turbines are an alternative to internal combustion engines. Turbines using LFG require a dependable gas supply for effective operation, and are generally suitable for landfills when gas production can generate at least 3 MW, or where sustainable LFG flow rates to the turbines are over approximately 1784 m^3/h at 50% CH_4. Typically, LFG-fired turbines have capacities greater than 5 MW [14]. Most LFG projects using turbines in the United States are in the 3–5 MW range, which require sustainable LFG flows in excess of 2000 m^3/h [16,18]. Advantages of this technology when compared to internal combustion engines include a greater resistance to corrosion damage, relatively compact size, and lower operation and maintenance costs. When compared with other generator options, turbines require additional power to run the plant's compression system [14]. Turbines are generally larger than internal combustion engines and are available in various sizes from 1 MW to more than 10 MW [18].

Microturbines can be used instead of internal combustion engines for LFG energy conversion. This technology generally works best for small scale recovery projects that supply electricity to the landfill or to a site that is in close proximity to the landfill. Single microturbine units have capacities ranging between 30 and 250 kW, and are most suitable for applications below 1 MW, or where sustainable LFG flow rates to the microturbines are below approximately 595 m^3/h at 50% CH_4. Sufficient LFG treatment is generally required for microturbines and involves the removal of moisture and other contaminants [14].

For LFG applications, fuel cells use hydrogen from CH_4 to generate electricity. Fuel cells have an advantage over combustion technologies in that the energy efficiency is typically higher without generating combustion byproducts such as NO_X, CO, and sulfur oxides (SO_X). If fuel cells are used to generate electricity from landfill CH_4, then a gas cleanup system is required to ensure that the catalyst within the fuel cell is not contaminated by trace constituents that are present in LFG. Trace constituents include sulfur and chlorine compounds which can inhibit performance and poison the catalyst [14].

In LFG technologies selection, a key factor is knowledge of LFG generation in the FDS. It is known that there are parameters affecting the LFG generation, including, the amount of waste disposed, waste composition, moisture content, temperature, and lag time in gas generation, among others [1,2,5,15,16,18–22]. Over the years a large number of numerical and mathematical models have been developed to estimate LFG (such as the tier-three method [23], the IPCC method [1,6,19,24,25], the EPA model [1,2,10,16], and the Mexico LFG Model [26], among others) based on zero, first, and second-order approaches. However, second-order models are not commonly used because the required parameters in each model are often so uncertain that they negatively affect the accuracy of the model outcomes [20]. Likewise, zero-order models do not reflect the biological LFG generation processes. Because of these limitations, simplified approaches have been developed based on first-order decay (FOD). The FOD model is widely used by industry, state regulators, the Intergovernmental Panel on Climate Change (IPCC) and the US Environmental Protection Agency (US EPA) to estimate LFG generation. Most of these models are based on two primary model parameters, an ultimate methane generation potential and a first-order decay rate constant [20,21].

The Mexico LFG Model uses a first-order decay equation that assumes that the biogas generation reaches its maximum after a period of time before methane generation. This model requires that the user enter specific data, such as the opening year, closing

year, annual waste disposal rates, annual rain precipitation, and collection system efficiency. The model estimates the biogas generation rate for each year using the first-order decay equation (see Eq. (1)), which was modified by the US EPA in the LandGEM model version 3.02 in 2005 [26].

$$Q_{LFG} = \sum_{t=1}^{n} \sum_{j=0.1}^{1} 2kL_0 \left[\frac{M_i}{10}\right](e^{-kt_{ij}})(MCF)(F) \quad (1)$$

where Q_{LFG} is the maximum expected biogas generation flow rate (m^3/yr), i is the increase in time of 1 yr, n is the year of calculated waste disposal from the initial year, j is the increase in time in 0.1 yr, k is the methane generation rate (yr^{-1}), L_0 is the methane generation potential (m^3/t), M_i is the mass of the solid waste disposal in the ith year (t), t_{ij} is the age of the jth section of the waste mass(M_i) disposed in the ith year (decimal years), MCF is the methane correction factor, and F is the fire adjustment factor.

The model automatically provides values for the methane generation rate and methane generation potential [26]. Despite having presets, these parameters can be modified according to the *in situ* characteristics.

Methane generation rate (k) represents the first-order biodegradation rate of the methane generated after the disposal of the waste in the FDS and is related to the lifetime of the waste. As the value of k increases, the methane generation in an FDS also increases (provided that the FDS is still receiving waste) and then decreases with time (after the FDS is closed) [15,25–27].

Several studies have indicated that typically the range of k values is from 0.02 for dry sites to 0.07 for wet locations [15,28]. The most rapid rates (k=0.2 or an average life of approximately 3 yr) are associated with conditions of high humidity and highly degradable materials, such as food waste. Slower rates (k=0.02 or a half-life of approximately 35 yr) are associated with dry conditions and slowly degradable materials, such as wood or paper [20,25].

In the version 2.0 Mexico LFG Model (MBM 2.0), the k values for the four categories of waste degradation are assigned (very fast, R^+; moderately rapid, R^-; moderately slow, L-; and very slow, L^+) for each of the five climatic regions of Mexico (see Table 1). These values vary based on the average annual precipitation in the region, where the FDS is located, and the type of waste disposed.

Methane generation potential (L_0) is the total amount of methane that can potentially be produced by a unit mass of waste when the waste has degraded and depends almost exclusively on the characterization of the residues in the FDS, in particular, the organic fraction of the material [15,20,25,26,28]. This value is estimated based on the carbon content of the residue, the biodegradable carbon fraction, and the stoichiometric conversion factor [28]. A higher content of cellulose corresponds to a greater value of L_0. L_0 units are in cubic meters per ton of waste (m^3/t). The theoretical values of L_0 vary from 6 to 270 m^3/t [1,20,26], and typical values of this parameter are between 125 and 310 m^3/t [28]. The US EPA uses the typical value of 170 m^3/t [2,15].

In MBM 2.0, L_0 values are assigned for the four categories of waste degradation (R^+, R^-, L^-, and L^+) for each of the five climatic regions of Mexico. These values vary according to the waste composition at the FDS, and it is assumed that these values remain constant for all climates, except for category 2, in which there is a change in climate due to differences in the type of local vegetation. The values for the climatic region where the Ensenada's sanitary landfill (SL) is located, (Region 5: Northwest and Northern Interior) are presented in Table 1.

Table 1
Values of k and L_0 in the northwest region & northern interior of Mexico.

Waste category	k	L_0
Residues with very rapid degradation (R^+)	0.100	69
Residues with moderately rapid degradation (R^-)	0.050	149
Residues with moderately slow degradation (L^-)	0.020	214
Residues with very slow degradation (L^+)	0.010	202

The objectives of this research are the following: (a) modify constants L_0 and k with *in situ* data, and (b) estimate the LFG generation in the Ensenada's SL with the modified constants. From the study, the amount of energy that could be generated from the decomposition of domestic solid waste (DSW) disposed in the Ensenada's SL, in Ensenada, Baja California, Mexico, can be determined.

2. Methodology

The study was conducted in the city of Ensenada, municipal seat of the municipality of the same name in the State of Baja California, located in northwestern Mexico. Ensenada, with a land area of 52,510.712 km^2, represents 74.84% of the state of Baja California and 2.6% of the country's area, and is the largest municipality in Mexico. Its location is at 31°52′ North latitude and 116°36′ West longitude. The average annual precipitation in Ensenada is 250 mm, with a Mediterranean-like climate, mild temperatures almost all year round and rainfall in the winter.

The biogas prediction was conducted in two stages: (1) the constants of the biogas generation were modified, and (2) the guidelines proposed by SCS Engineers [26] for MBM 2.0 were followed.

2.1. Modification of the biogas generation constants

To modify the constants of the LFG model, the following were required: (a) waste characterization studies for a year in two seasonal periods (winter and summer), (b) biogas extraction tests, (c) observations of the characteristics and operation of SL, (d) interviews with the site managers, and (e) several IPCC model parameters.

2.1.1. Waste characterization

The characterization study was conducted for five consecutive days in 2 months (February and June) during 2009 in the city of Ensenada. Two periods were required because the annual waste composition needed to be known, and the climate of the study area is Mediterranean-like. The selected months represent each season. The analyzed residues were deposited in the SL by the municipality-run waste collection trucks. The samples sizes were approximately 260 kg per day, greater than the amount proposed by the Mexican Standard NMX-AA-015-1985 [29] but in accordance with other studies [30,31]. Subsequently, the samples were categorized, weighed, and recorded. For the record, the byproducts were quantified with the registration form from the Mexican Standard NMX-AA-022-1985 [32]. The byproducts were grouped into 14 categories, as proposed by SCS Engineers [26]. These byproducts are food, paper and cardboard, yard trimmings, wood, rubber, leather, bones and straw, textiles, toilet paper, other organic diapers, metal, construction and demolition, glass and ceramics, plastics, and other inorganic materials.

2.1.2. Biogas extraction tests

The equipment used for the biogas extraction tests included an analyzer and gas extraction monitor GEM™2000 designed by LANDTEC. For each sampling point, the equipment measured the biogas composition (CH_4, CO_2, O and N), temperature, static and differential pressures, biogas flow, and the heat content of each sample. On the site, the GEM™2000 was connected to the head Accu-Flo LANDTEC 2V to perform readings. Readings were

Fig. 1. Biogas test in venting wells.

performed in four of the 12 installed wells for 7 days each month over a period of 3 months (September, October and November). Due the construction shape of the SL (see Fig. 1), the wells were selected based on their ease of access. For each sampling day, three readings were taken at each well during the day (primarily biogas composition and temperature), and these data were recorded in the DataField CS Software version 3.02L.

In order to identify with greater certainty whether there are a significant difference between seasons, was performed an experiments Design Randomized Complete Block (RCBD) with data from the biogas flow (m^3/h) of the landfill. This data were obtained in 3 representative months according to the climate in the city of Ensenada (summer: September, month of transition: October, and winter: November). Were considered an average observation per treatment in each block and the order in which treatments are run within each block was randomly determined. The months were considered as treatments and the wells as block. For analysis was used the statistical software MINITAB®14.1 using a reliability of 95%.

The statistical model of RCBD [33] shown in Eq. (2).

$$y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \tag{2}$$

where y_{ij} is the response of the jth treatment in the ith block, μ is the overall mean, τ_i is the effect on the ith block, β_j is the effect of the jth treatment of the factor, and ε_{ij} is the random error associated with the ith block and the jth treatment of the factor.

2.1.3. *Determining the in situ constants*

At this stage of the methodology, the constants k and L_0 were determined according to the *in situ* characteristics. For this, *in situ* observations were done during the months of June, August and September. In addition, interviews were conducted with the general manager and operations manager of the company that manages the granting of the SL. This information was used to determine the constants and to estimate the LFG generation.

The constant k provided by the MBM 2.0 was modified with the percentage of waste that is included within each category of waste (see Eq. (3)).

$$k_{weighted} = \sum_{i=1}^{9} (\%r_i \times vp) \tag{3}$$

where $\%r_i$ is the percentage of waste in each category and vp is the k value predetermined by the MBM 2.0 in each of the degradation categories.

Table 2
Methane correction factor.

Management site	Depth < 5 m	Depth ≥ 5 m
Without management	0.4	0.8
With management	0.8	1.0
Semi-aerobic	0.4	0.5
Condition unknown	0.4	0.8

To determine L_0, the IPCC methodology [8,25,27] was used, shown in Eq. (4).

$$L_0 = MCF \times DOC \times DOC_F \times F \times \frac{16}{12} \tag{4}$$

where L_0 is the generation potential, *MCF* is the correction factor for methane, *DOC* is the degradable organic carbon (fraction), DOC_F is the fraction of degradable organic carbon assimilated, F is the fraction of CH_4 in the biogas, and 16/12 is the stoichiometric constant.

The following describes the equations to determine the parameters described above:

MCF (*methane correction factor*). This is an adjustment to the estimated biogas generation in the model that takes into account the degree of anaerobic degradation of waste. The *MCF* varies depending on the depth of the waste and landfill type as defined by management practices. Table 2 summarizes the *MCF* values applied by the model [6,9,19,25,26,34].

DOC (*degradable organic carbon*). The *DOC* content is expressed in Eq. (5) and is essential in the calculation of the methane generation, which depends on the composition of the waste and varies from city to city [8,9,34].

$$DOC = 0.40(A) + 0.17(B) + 0.15(C) + 0.30(D) \tag{5}$$

where A is the percentage of residues corresponding to paper, cardboard, and textiles; B is the percentage of residues corresponding to garden waste, park waste, or other putrescible organic waste (other than food); C is the percentage of residues corresponding to residues from food; and D is the percentage of residues corresponding to wood and straw.

DOC_F (*fraction of degradable organic carbon assimilated*). This is a portion of the *DOC* that is converted into biogas (see Eq. (6)). The estimation is based on the theoretical model that varies only with temperature in the anaerobic zone of a landfill [9,27].

$$DOC_F = 0.014T + 0.28 \tag{6}$$

where T is the temperature in centigrade degree (°C)

F (*fraction of CH_4 in landfill gas*). The fraction of methane in the biogas is assumed to be 0.5 because biogas is mainly composed of 50% CH_4 and 50% CO_2 with less than 1% of other trace constituents [9,25,27].

2.2. Estimating biogas generation

To estimate the biogas generation in Ensenada's SL, Eq. (1) of MBM 2.0 developed by SCS Engineers was used [26]. Inputs into the model included information about *in situ* observations and interviews, such as the following: (1) annual disposal of municipal solid waste (MSW) from most recent year, (2) years when the SL opened and closed, (3) estimated annual increase of disposal, (4) average depth of the SL, (5) fires in the SL, (6) percentage of area with waste with daily cover, intermediate and final, (7) the percentage of waste area having a clay/geomembrane, (8) compact waste, (9) leached outcrops at the surface of the SL, and (10) waste composition. The Excel® spreadsheet published by SCS Engineers [26] was modified using the values of the constants k and L_0.

3. Results and discussion

The following sections show the results of the characterization of the domestic solid waste from the city of Ensenada, the average percentage of methane and SL's average temperature obtained in the biogas extraction tests, and projected biogas generation in the SL. For the DSW characterization, 10 samples of approximately 260 kg/day were taken, and thus, a total weight of 2511.35 kg from all samples was analyzed. A total of 247 readings were taken during the biogas tests.

3.1. Modification of the biogas generation constants

The constants were modified in three phases: (1) DSW characterization, (2) biogas extraction tests, and (3) determination of the *in situ* constants.

3.1.1. Waste characterization

The total weight of the samples was 2511.35 kg, out of which 1379.66 kg was obtained in February and 1131.69 kg was obtained in June (winter and summer, respectively). Table 3 shows the composition of the DSW in the two seasons in the city of Ensenada. It can be seen that the percentages of the organic and inorganic components are 68.57% and 30.30%, respectively.

3.1.2. Biogas extraction tests

A total of 247 readings were obtained in the 3 months sampled, higher quantity from those conducted by SCS Engineers in different FDS in Mexico and Latin America [35–40]. The biogas composition showed, on average, 44% methane at an average temperature of 38.14 °C. Table 4 shows the average biogas composition data obtained from September to November 2009.

It can be seen from the results (see Table 4) that the third well had a higher concentration of CH_4 and decreased in October, which is when the weather begins to change in Ensenada. However, the concentration of the third well stabilized in November when the temperature did not vary much. It is important to note that the third well had the greatest depth of the three wells and the highest percentage of CH_4. This fact is consistent with other research [12], which report that the deeper the well, the greater the methane generation.

The results from RCBD analysis show no statistically signifi cant difference (p-value > 0.05) between seasons in the biogas generation in the Ensenada's SL. This means that average flow of biogas generated by months tends to be similar. Moreover, the coefficient of determination (R^2) shows that the model explains 85% of the variance in the flow of biogas, indicating that model fits the data adequately. When is performed an extrapolation considering the data collected in the 3 months in SL, is possible observe that the model provides values close. *E.g.* the readings average were 55.47 m^3/h per month, this is a total of 665.68 m^3/h annually. This value has a difference smaller than the 2.2% for value projected by the model.

Table 3
Annual average of the DSW composition in Ensenada.

Byproducts of DSW	Kilograms (kg)	Percentage (%)
Food	909.08	36.20
Paper and cardboard	285.27	11.36
Yard trimming	80.35	3.20
Wood	8.71	0.35
Rubber, skin, bones and straw	5.44	0.22
Textiles	156.60	6.24
Toilet paper	269.33	10.72
Other organics	6.97	0.28
Diapers	146.34	5.83
Metals	64.39	2.56
Construction and demolition	17.99	0.72
Glass and ceramics	118.89	4.73
Plastics	309.87	12.34
Others inorganics	132.12	5.26
Total	**2511.35**	**100.00**

Table 4
Averages in the biogas samples generated in Ensenada's SL.

Month	Well	Percentage (%)				Temp. (°C)	Biogas flow (m^3/h)	Heat potential (kW)
		CH_4	CO_2	O_2	N_2			
September	1	31.20	24.44	8.61	35.75	32.84	11.62	37.29
	2	40.26	32.06	5.09	22.59	38.33	16.00	66.57
	3	55.37	44.00	0.23	0.40	45.80	14.01	81.14
	4	48.51	38.94	2.36	10.20	41.26	12.50	60.87
October	1	33.58	26.61	7.92	31.90	31.69	11.88	41.88
	2	54.94	44.68	0.21	0.17	45.88	17.13	98.52
	3	39.17	31.16	5.96	23.71	36.91	14.60	59.57
	4	48.43	38.71	2.72	10.13	41.26	9.98	51.41
November	1	36.88	28.55	6.96	27.62	30.67	14.85	56.33
	2	37.52	28.91	7.03	26.54	34.31	16.18	63.67
	3	54.99	44.49	0.37	0.15	44.49	15.76	90.55
	4	48.17	37.96	3.07	10.81	39.14	11.78	58.44

3.1.3. Determining the in situ constants

In this stage, the constants k and L_0 were determined according to *in situ* characteristics. For the estimation, were used the results of the waste characterization, the biogas extraction test data, and *in situ* observations.

Methane generation rate (k). This constant was determined using Eq. (3), and its value was of 0.0482 yr^{-1} (see Table 5). This value is within ranges reported in others research. Amini et al. [20] point out a range of 0.04–0.09 yr^{-1}, Thompson et al. [8] reported values for Canadian landfills in the range of 0.023–0.056 yr^{-1}, and Amini et al. [21] mentioned values in the range from 0.01 to 0.21 $yr^{-1}$with 0.04 yr^{-1} as a commonly applied value.

Methane generation potential (L_0). This constant was determined using Eq. (4), and its value was 94,457 m^3/t. This value is consistent with the values established by Amini et al. [20] who indicated a range from 93 to 140 m^3/t. However, it is smaller than

Table 5
Determination of k according to the site.

Waste category	Percentage of waste (%)	Category degradation	Value k [a] Region 5	Modified value of k
Food	36.2	R^+	0.10	0.0362
Paper and cardboard	11.4	L^-	0.02	0.0023
Trimming (garden)	3.2	R^-	0.05	0.0016
Wood	0.4	L^+	0.01	0.0000
Rubber, skin, bones and straw	0.2	L^+	0.01	0.0000
Textiles	6.2	L^-	0.02	0.0012
Toilet paper	10.7	R^-	0.05	0.0054
Other organics	0.3	R^+	0.10	0.0003
Diapers (assuming 20% organic/80% inorganic)	5.8	R^+	0.10	0.0012
Metals	2.6	Inert	–	–
Construction and demolition	0.7	Inert	–	–
Glass and ceramics	4.7	Inert	–	–
Plastics	12.3	Inert	–	–
Others inorganics	5.3	Inert	–	–
			k weighted	**0.0482**

[a] Values determined in MBM 2.0

Table 6
DOC determination according to the site.

Waste category	Percentage of waste (%)	Category (A, B, C or D)	Value DOC
Food	36.2	0.15	0.0543
Paper and cardboard	11.4	0.40	0.0454
Trimming (garden)	3.2	0.17	0.0054
Wood	0.4	0.30	0.0011
Textiles	6.2	0.40	0.0250
Toilet paper	10.7	0.40	0.0429
		Total	**0.1741**

that established by Amini et al. [21] (56–77 m^3/t) in five landfills in Florida. The difference regarding the latter may be because all landfills were located in Florida which has relatively high annual precipitation rates, thus increases waste moisture content. This trend is showed also in the results from a study of tropical landfills by Machado et al. [1], who specified a L_0 of 70 m^3/t based on both laboratory and on-site measurements.

The values of the parameters in Eq. (4) (value of L_0) were obtained as follows:

MCF (*methane correction factor*). This value is equal to 1 because the site is considered with management. That is, the waste disposal at the site is controlled (waste direct to a disposal specific area, scavengers control and fire control), daily cover material is applied, and 75% mechanical compacting and residues leveling is done.

DOC (*degradable organic carbon*). Using Eq. (5), this value is estimated to be 0.1741, Table 6 shows in detail its estimation. This value is consistent with that established by Tsai [19] of 0.17, and is also found in the default value ranging from 0.08 to 0.21 set by Johari et al. [6].

DOC_F (*fraction of degradable organic carbon assimilated*). An average temperature of 38.14 °C was observed from the biogas extraction test; by substituting this temperature into Eq. (6), we obtained a value of 0.8140 DOC_F. This value is greater than the default value used by the IPCC is 0.77 [19,27]. However, this factor can range from 0.42 at 10 °C to 0.98 at 50 °C. In fact, in many deep fills (greater than 20 m), recorded temperatures have been greater than 50 °C, which is clearly an anaerobic condition [27].

F (*fraction of CH4 in landfill gas*). The fraction of methane in the biogas is assumed to be 0.5 because the extraction biogas test gave an approximate percentage of 44% methane.

Table 7
LFG predictions in Ensenada's SL with modified constants (k=0.048 yr^{-1} L_0=94.457 m^3/t).

Year	Estimated LFG generation (m^3/h)	LFG recuperation estimated (m^3/h)	Maximum power of plant (MW)
2009	681	450	0.7
2010	821	542	0.9
2011	963	636	1.1
2012	1107	731	1.2
2013	1254	828	1.4
2014	1404	927	1.5
2015	1558	1028	1.7
2016	1715	1132	1.9
2017	1876	1238	2.0
2018	2042	1348	2.2
2019	2213	1460	2.4
2020	2109	1392	2.3
2021	2009	1326	2.2
2022	1915	1264	2.1
2023	1825	1204	2.0
2024	1739	1148	1.9
2025	1657	1094	1.8

The maximum capacity of the power plant assumes that the gross heat index is 10,800 Btus/kWh (hhv)

3.2. Estimation of biogas in Ensenada's SL

The following inputs used in the model were the *in situ* observations and interviews with the site manager: (1) the annual disposal of the MSW in 2009 was 132,055 t, (2) the SL operations began in 2004 and its closure will be in 2018, (3) there have been no fires in the SL, (4) the average depth of each cell is 15 m, (5) before depositing waste, a low-permeability geomembrane coat is installed, (6) the deposited waste is covered daily, where only two closed cells have final cover, (7) the waste is 75% compacted, and (8) leached outcrops were not observed. The estimated annual increase in waste disposal in Baja California according to the quantities reported by the SEMARNAT [41] in 2008 is 5%.

With the above information, the modified constants (k=0.0482 and L_0=94.457), Eq. (1), and the modified spreadsheet Excel® published by SCS Engineers [26], the LFG predictions for Ensenada's SL were determined, as shown in Table 7. It can see that Ensenada's SL will reach a maximum capacity of 2.40 MW in the year following the closure year (2019). Then, the capacity will decrease approximately 0.10 MW ever year. This decrease occurs because the model [26] assumes that the maximum generation normally occurs in the

closing year or the following year, and the LFG generation decreases exponentially as the organic fraction of the waste is consumed. The concentration in the biogas decreases with the age of the SL; this fact is included in the model with the k and L_0 parameters. This trend is also reported by Thompson et al. [8].

The comparison of the results of the LFG generation with the modified constants shows that in 2009, the plant generated 78.74% more than the results obtained by the SCS Engineers [42] in Ensenada's closed landfill. However, this estimate was obtained using the Mexican LFG Model version 1.0, where the k and L_0 values were obtained based on the waste composition provided by the municipality of a study conducted in 2002. The characterization study is 8 yr old, and during this time, the consumption patterns have increased together with the k and L_0 values from the default system; however, in this investigation, these values were obtained *in situ*.

Using *in situ* values (modified constants k and L_0) provide a more accurate result than what the model gives, which assumes the values according to a region. In other studies [43], different values of k and L_0 have been reported in four distinct populations within the same region and thus, a single value for a region cannot be assumed. This is also reported for Canada by Thompson et al. [8]. Moreover, despite the IPCC attempt to establish a suitable universal method, countries still use different methods for collecting and reporting their methane production due to lack of validation of models and no model being accurate over a range of conditions. A validated model is needed to facilitate a standardized methodology.

The potential for the power generation that could be obtained using the LFG generated in the Ensenada's SL is 4.36% of the capacity already installed in Ensenada in 2004. For this quantity, it was assumed that the overall efficiency of the internal combustion engine was 81% and that the capture efficiency of the biogas was 66%. This energy could be used for street lighting, which used 13,997 MW/h of the 21,235 MW/h reported for 2010 in the Statistical Yearbook of Baja California, edition 2011 (approximately 66% of the energy required). Considering the rate of 2.426MX$/kWh (0.187US$/kWh), there would be a savings of approximately US$2.62 million.

Other studies in Mexico on LFG generation have shown higher values than those obtained in this investigation, as in the case of Chihuahua's SL [35], where the SCS Model (modified version of the EPA) was used and the waste composition comparison was based on typical percentages of the US. In this landfill, the LFG recovery was estimated at 2013 m^3/h in 2009, increasing to 2610 m^3/h in 2013, and decreasing to 1581 m^3/h in 2019. In Queretaro's SL [36], the previous model was used and the typical waste percentage of the US. In this study, the LFG recovery was estimated at 1954 m^3/h in 2009, increasing to 3277 m^3/h in 2016, and decreasing to 2319 m^3/h in 2019. There is another study conducted in SIMEPRODESO SL in Monterrey, Mexico [44]; however, they used the “USEPA E-PLUS” model, a different methodology to evaluate the LFG recovery.

In other countries, a study conducted in the landfill located in Volos, Greece, showed in the year following the closing (2003), the largest biogas recovery (1390 m^3/h). At another site located 20 km east of Heraklion (Fodele region), an LFG recovery of 1851 m^3/h was reported in 2007 [2]. Unlike the present study, in both projections, the LandGEM mathematical model version 3.02 with value presets $k=0.05$/yr and $L_0=170$ m^3/t was used. Also, the annual waste disposals were lower, which was 70,000 t in Volos and 100,000 t in Heraklion. Additionally, these landfills are closed, unlike the present study that is still an active landfill.

4. Conclusions

Information at landfill sites helps to more accurately predict the parameters required for the estimation of LFG generation and use the waste generated as a renewable energy source. A major factor for the estimation is to know the current waste composition at the site. This study showed that the waste of the city of Ensenada has an organic component of approximately 70%, a factor that directly influences the values of k and L_0.

The power generation with modified constants ($k=0.0482$ and $L_0=94.457$) show an increase of 26% compared with predictions with the default data. It is also important to mention the positive environmental consequences that would occur using the LFG in Ensenada's SL. The potential reduction in CO_2e emissions that would not be released into the atmosphere is approximately 1,168,684 t CO_2e during the period 2009–2025. This volume has a total value of US$11.69 million in the carbon market, considering as reference [11], an average cost of US$11.00 CO_2e/t.

Although the best projection is done using site information, there are great gaps in literature regarding the constants used in predicting LFG generation. It is known that several factors and the complexity of the system cannot be measured. Therefore, it is important to have standardized criteria for performing valid comparisons when evaluating LFG recovery. To date, there are no studies that verify the model being applied is accurate, and thus, it is important to make projections with site investigation data because these data will more accurate predictions.

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